A novel explanation of charmonium-like structure in $e^+e^- \to \psi(2S)\pi^+\pi^-$

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(Dated: March 28, 2011)

We first present a non-resonant description to charmonium-like structure $Y(4360)$ in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process. The $Y(4360)$ structure is depicted well by the interference effect of the production amplitudes of $e^+e^- \to \psi(2S)\pi^+\pi^-$ via the intermediate charmonia $\psi(4160)/\psi(4415)$ and direct e^+e^- annihilation into $\psi(2S)\pi^+\pi^-$. This fact shows that $Y(4360)$ is not a genuine resonance, which naturally explains why $Y(4360)$ was only reported in its hidden-charm decay channel $\psi(2S)\pi^+\pi^-$ and was not observed in the exclusive open-charm decay channel or R-value scan.

PACS numbers: 14.40.Pq, 13.66.Bc

With the observations of charmonium-like states X, Y, Z by experiment, studying charmonium-like states X, Y, Z has became an intriguing and important research topic in hadron physics at present. The initial-state radiation (ISR) processes $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$ and $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$ are the ideal platform to carry out the study of charmonium-like states with $J^{PC}=1^{--}$. Besides the first observation of the $Y(4260)$ structure in $e^+e^- \to \gamma_{ISR}J/\psi\pi^+\pi^-$ announced by BaBar [1] and confirmed by the CLEO and Belle Collaborations [2–4], a new charmonium-like structure $Y(4360)$ was reported at BaBar [5] by analyzing the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum of $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$. Later, Belle confirmed BaBar's result and also announced another structure $Y(4660)$ in $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$ [6].

These observations of $Y(4360)$ and $Y(4660)$ not only make the vector charmonium-like structures in ISR processes become abundant, but also stimulate theorist's interest in revealing their underlying structure. Ding *et al.* indicated that $Y(4360)$ could be as a $n^{2S+1}J_L = 3^3D_1$ charmonium state or a charmonium hybrid while $Y(4660)$ is a good candidate of charmonium with $n^{2S+1}J_L = 5^3S_1$ [7]. With these possible structure assignments, the corresponding decay behaviors of $Y(4360)$ and $Y(4660)$ are given [7]. Under the same charmonium assignments to $Y(4360)$ and $Y(4660)$ as that in Ref. [7], the di-electron widths of $Y(4360)$ and $Y(4660)$ are obtained [8]. With screened potential, Li and Chao calculated the mass spectrum of charmonium, which explained $Y(4360)$ and $Y(4660)$ as $\psi(3D)$ and $\psi(6S)$ charmonia respectively and predicted their decay behaviors [9]. In Ref. [10], $Y(4360)$ was also explained as a $4S$ charmonium state. The baryonium assignments to $Y(4360)$ and $Y(4660)$ were proposed in [11], where $Y(4360)$ might be the radial excited state of $Y(4260)$ and $Y(4660)$ is the radial excited state of the C-spin singlet with the flavor wave function $(|\Lambda_c^+\Lambda_c^-\rangle + |\Sigma_c^0\bar{\Sigma}_c^0\rangle)/\sqrt{2}$, which in fact are a extension of former $\Lambda_c^+\Lambda_c^-$ baryonium explanation to $Y(4260)$ [12]. Associated with the charmonium-like state $Y(4630)$ in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [13] with $Y(4660)$, Cotugno *et al.* suggested that both $Y(4630)$ and $Y(4660)$ are from the same charmed baryonium state [14]. The authors in Ref. [15] indicated that the vector hybrid charmonium with strong coupling with D^*D_0 channel results in considerable threshold attraction related to $Y(4360)$. By the QCD sum rule, Albuquerque and Nielsen calculated the masses of $(c\bar{c}q\bar{q})$ or $(c\bar{c}s\bar{s})$ states with $J^{PC}=1^{--}$, and found that $(c\bar{c}s\bar{s})$ state with obtained mass 4.65 GeV corresponds to $Y(4660)$ while $Y(4360)$ could be as a $D_0\bar{D}^{*0}$ molecular state [16]. Later, the mass of the P-wave cs-scalar-diquark $\bar{c}\bar{s}$-scalar-antidiquark state was computed in the framework of the QCD sum rule. The result 4.64 ± 0.25 GeV is in good agreement with the experimental value of $Y(4660)$ [17]. With the obtained effective potential of $D^*\bar{D}_1$ system in Refs. [18, 19], Close *et al.* explained $Y(4360)$ as a $2S$ $D^*\bar{D}_1$ molecular state [20, 21]. $Y(4660)$ as an $f_0(980)\psi(2S)$ bound state was proposed [22, 23] and studied [24].

Although different explanations for $Y(4360)$ and $Y(4660)$ were given from the point of view of conventional charmonium or exotic state just summarized in the above, the current situation regarding the 1^{--} charmonium-like structures $Y(4360)$ and $Y(4660)$ produced through ISR process is clearly unsettled [16]. No matter what explanations we proposed, we can not avoid the fact that there is not any evidence of these 1^{--} charmonium-like structures produced through ISR process in the exclusive open-charm decay channel [25–31] and R-value scan [32].

Recently, we proposed a new approach different from conventional charmonium and exotic state explanations to explain $Y(4260)$ structure, where $Y(4260)$ is not a genuine resonance [33]. $e^+e^- \to J/\psi\pi^+\pi^-$ can occur

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directly via e^+e^- annihilation. In addition, the intermediate charmonia can contribute to $e^+e^- \to J/\psi\pi^+\pi^-$, where we choose $\psi(4160)$ and $\psi(4415)$ as intermediate charmonia since the $Y(4260)$ structure is just sandwiched by two known charmonia $\psi(4160)$ and $\psi(4415)$. The interference effect from the above two production mechanisms for $e^+e^- \to J/\psi\pi^+\pi^-$ can reproduce the $Y(4260)$ structure in the $J/\psi\pi^+\pi^-$ invariant mass spectrum of the $e^+e^- \to J/\psi\pi^+\pi^-$ process well [33]. Such non-resonant explanation can naturally answer why experiment only reported $Y(4260)$ in its hidden-charm decay channel.

Successfully explaining $Y(4260)$ structure stimulates our interest in extending the same picture to describe the charmonium-like structures observed in $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$ since the experimental situation of $Y(4360)$ is similar to that of $Y(4260)$. If the $Y(4360)$ structure also be depicted by the non-resonant explanation similar to that proposed in our former work [33], it not only further supports non-resonant explanation to $Y(4260)$ but also deepens our understanding of the underlying mechanism resulting in these charmonium-like structures produced via ISR process.
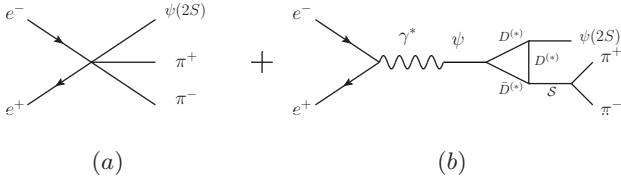

FIG. 1: The diagrams depicting the $e^+e^- \to \psi(2S)\pi^+\pi^-$ production process. (a) The e^+e^- annihilation directly into $\psi(2S)\pi^+\pi^-$. (b) The contributions from intermediate charmonia to $e^+e^- \to \psi(2S)\pi^+\pi^-$. Here, the hadronic loop effect plays important role to the $\psi \to \psi(2S)\mathcal{S}$ transition.

In general, the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process occurs via two mechanisms. One is the direct production of $\psi(2S)\pi^+\pi^-$ by e^+e^- annihilation (Fig. 1(a)), which can be depicted by the production amplitude

$$\mathscr{A}_{NoR} = g_{NoR}\bar{u}(-k_1)\gamma_\mu u(k_2)\epsilon_{\psi(2S)}^\mu(k_5)\,\mathcal{F}_{NoR}(s), \quad (1)$$

where the form factor $\mathcal{F}_{NoR}(s)$ is introduced to represent the s-dependence of $\psi(2S)\pi^+\pi^-$ production directly via the e^+e^- annihilation, which can be represented as $\mathcal{F}_{NoR}(s) = \exp\left(-a(\sqrt{s} - \sum_f m_f)^2\right)$ with $\sum_f m_f$ as the sum of the masses of the final states for $e^+e^- \to \psi(2S)\pi^+\pi^-$. In Eq. (1), two parameters a and coupling constant g_{NoR} are introduced. $\sqrt{s}$ is the energy of center of mass frame of e^+e^-. k_1, k_2, k_5 correspond to the four momenta of e^+, e^-, $\psi(2S)$, respectively.

Another is from intermediate charmonium contribution shown in Fig. 1(b), where e^+ and e^- annihilate into one virtual photon, which interacts with vector charmonium. Then, charmonium transits into $\psi(2S)\pi^+\pi^-$. Since two well-known charmonia $\psi(4160)$ and $\psi(4415)$

are most close to $Y(4360)$ among these observed charmonia, we choose $\psi(4160)$ and $\psi(4415)$ as the intermediate states to $e^+e^- \to \psi(2S)\pi^+\pi^-$ process. Under the vector meson dominance (VMD) mechanism [34, 35] for the $\gamma \to \psi(4160)/\psi(4415)$ coupling, the general amplitude of $e^+(k_1)e^-(k_2) \to \psi(2S)(k_5)\pi^+(k_3)\pi^-(k_4)$ via the intermediate charmonia reads as

$$\begin{aligned}\mathscr{A}_{\psi,\mathcal{S}} &= \bar{u}(-k_1)e\gamma^\mu u(k_2)\frac{e\,m_\psi^2/f_\psi\,\epsilon_{\psi(2S)}^\rho}{(k_1+k_2)^2 - m_\psi^2 + im_\psi\Gamma_\psi}\\ &\times\left[g_A^\psi g_{\nu\rho}k_5\cdot(k_3+k_4) + g_B^\psi k_{5\nu}(k_{3\rho}+k_{4\rho})\right]\\ &\times\frac{-g_\mu^{\ \nu}}{(k_1+k_2)^2}\frac{g_{\mathcal{S}\pi\pi}(k_3\cdot k_4)}{(k_3+k_4)^2 - m_\mathcal{S}^2 + im_\mathcal{S}\Gamma_\mathcal{S}} \quad (2)\end{aligned}$$

with the decay constant f_ψ of intermediate charmonium and the coupling constant $g_{\mathcal{S}\pi\pi}$ of scalar state interacting with dipion, where we assume $\pi^+\pi^-$ from scalar σ and $f_0(980)$ states which is consistent with the measurement result of the $\pi^+\pi^-$ invariant mass spectrum in $e^+e^- \to \psi(2S)\pi^+\pi^-$ [6]. Thus, in Eq. (2) we set $\psi = \{\psi_1 = \psi(4160), \psi_2 = \psi(4415)\}$ and $\mathcal{S} = \{\sigma, f_0(980)\}$. In Eq. (2), the coupling constants g_A^ψ and g_B^ψ are relevant to the transition of intermediate charmonium coupling to $\psi(2S)\mathcal{S}$, which are determined by evaluating hadronic loop mechanism [36–40]. Here, g_A^ψ and g_B^ψ are the functions of β_1 and β_2 respectively, where we adopt $\beta_1 = \beta_2 = 1$ [41], which are the parameters from the introduced form factor in hadronic loop calculation (see Ref. [33] for more details and the input parameters)

We write out the total amplitudes for $e^+e^- \to \psi(2S)\pi^+\pi^-$

$$\begin{aligned}\mathscr{A}_{tot} &= \mathscr{A}_{NoR} + e^{i\phi_1}\left(\mathscr{A}_{\psi_1,\sigma} + e^{i\phi_s}\mathscr{A}_{\psi_1,f_0}\right)\\ &\quad + e^{i\phi_2}\left(\mathscr{A}_{\psi_2,\sigma} + e^{i\phi_s}\mathscr{A}_{\psi_2,f_0}\right)\\ &\equiv \mathscr{A}_{NoR} + \mathscr{A}_{\psi_1} + \mathscr{A}_{\psi_2} \quad (3)\end{aligned}$$

with three introduced phase angles ϕ_1, ϕ_2, ϕ_s. Generally speaking the phases between different Feynman diagrams are fixed and not arbitrary as they are in this work. However, there maybe exist hadronic loop effects which generate different phases among the different diagrams (because the momentum flow is different). Hence it is permissible to parameterize our ignorance of these interactions with these arbitrary phases to be fitted as is done in this work [33]. The observable is proportional to the modulus square of production amplitude $\mathscr{A}_{tot}$, which includes the squared amplitudes ($|\mathscr{A}_{NoR}|^2$, $|\mathscr{A}_{\psi_1}|^2$, $|\mathscr{A}_{\psi_2}|^2$) and the cross terms ($2\text{Re}(\mathscr{A}_{\psi_1}\mathscr{A}_{NoR}^*)$, $2\text{Re}(\mathscr{A}_{\psi_2}\mathscr{A}_{NoR}^*)$, $2\text{Re}(\mathscr{A}_{\psi_2}\mathscr{A}_{\psi_1}^*)$), where such cross terms reflect the interference effect just mentioned above.

With the above preparation, in the following we investigate whether the experimental data given by BaBar and Belle [5, 6] can be recovered by our model, where five parameters listed in Table I are applied to fit the

experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-$ at BaBar and Belle.

As shown in the last diagram of Fig. 2, we obtain the best fit (red solid line) for the experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-$, where the obtained central values with errors of the fitting parameters are listed in Table I, which indicate that the theoretical line shape of $e^+e^- \to \psi(2S)\pi^+\pi^-$ is not sensitive to the changes of the fitting parameters. Thus, our theoretical study indicates that the $Y(4360)$ structure in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum is reproduced well under the interference effect proposed in this work.

For explicitly illustrating the evolution of, we present how the $Y(4360)$ signal in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is depicted by adding the intermediate charmonia $\psi(4160)/\psi(4415)$ and considering the interference effect in a stepwise fashion, which is given by the remaining five diagrams in Fig. 2. Here, the obtained fitting parameters (see Table I) corresponding to the best fit are adopted. We notice that the interference of production amplitudes of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ processes via direct e^+e^- annihilation and through the intermediate charmonia $\psi(4160)/\psi(4415)$ plays a crucial role if fitting experimental line shape of the $Y(4360)$ structure. Describing the $Y(4360)$ structure well in our model shows that the $Y(4360)$ structure in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is not genuine resonance, which naturally explains why there is no any evidence of $Y(4360)$ in the exclusive open-charm process and R-value scan. As announced by Belle, there is another structure $Y(4660)$ besides $Y(4360)$ in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum. Our study shows that the $Y(4660)$ structure can not described by the interference effect just mentioned in this work. Revealing the property of $Y(4660)$ is still an intriguing research topic.

TABLE I: The values of parameters for the best fit (the red solid line shape in Fig. 2) to the experimental data. Here, GeV^{-2} and GeV^{-1} are as units of a and g_{NoR} respectively.

Parameter	Value	Parameter	Value (Rad)
a	4.9248 ± 0.4105	ϕ_1	2.6770 ± 0.1260
g_{NoR}	0.0074 ± 0.0009	ϕ_2	1.8509 ± 0.3010
		ϕ_s	0.0003 ± 0.2467

The whole picture of the $Y(4360)$ structure proposed in this letter is an important extension of that for the $Y(4260)$ structure in $e^+e^- \to J/\psi\pi^+\pi^-$, where $Y(4260)$ is also not genuine resonance [33]. If comparing the experimental information of $Y(4360)$ and $Y(4260)$, one notices that both $Y(4360)$ and $Y(4260)$ were observed in exclusive hidden-charm decay channel by ISR process, where $Y(4360)$ and $Y(4260)$ correspond to $\psi(2S)\pi^+\pi^-$ and $J/\psi\pi^+\pi^-$ channels respectively, which reflects the small difference between $Y(4360)$ and $Y(4260)$. To some extent, such non-resonant picture for $Y(4360)$ not only embodies the similarity between $Y(4360)$ and $Y(4260)$,

but also supports $Y(4260)$ non-resonant explanation in Ref. [33].

In summary, stimulated by the observation of charmonium-like structure $Y(4360)$ in the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process, in this letter we first propose a novel non-resonant explanation to the underlying structure of $Y(4360)$, which is different from the previous conventional charmonium or exotic explanations. The $Y(4360)$ structure is obtained by the interference effect of the production amplitude of $e^+e^- \to \psi(2S)\pi^+\pi^-$ via the intermediate charmonia $\psi(4160)/\psi(4415)$ and direct e^+e^- annihilation into $\psi(2S)\pi^+\pi^-$. Such picture provides a natural explanation of why experiment did not find any evidence of $Y(4360)$ in the exclusive open-charm decay process and R-value scan. Furthermore, the study presented in this letter further deeps our understanding of charmonium-like structures observed in hidden-charm process.

This study can be extended to include the theoretical study of other charmonium-like structures appearing in other hidden-charm processes from e^+e^- annihilation by ISR mechanism. Recently, the CLEO-c Collaboration announced a preliminary result by studying $e^+e^- \to h_c\pi^+\pi^-$, where there is a suggestive rise at 4260 MeV in the $h_c\pi^+\pi^-$ invariant mass spectrum [43]. Thus, we expect more experimental measurements especially to $e^+e^- \to h_c\pi^+\pi^-$. In addition, carrying out the study of the remaining charmonium-like structure $Y(4660)$ [6] in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum will be also an intriguing and valuable research topic by associating with charmonium-like structure $Y(4630)$ in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [13].

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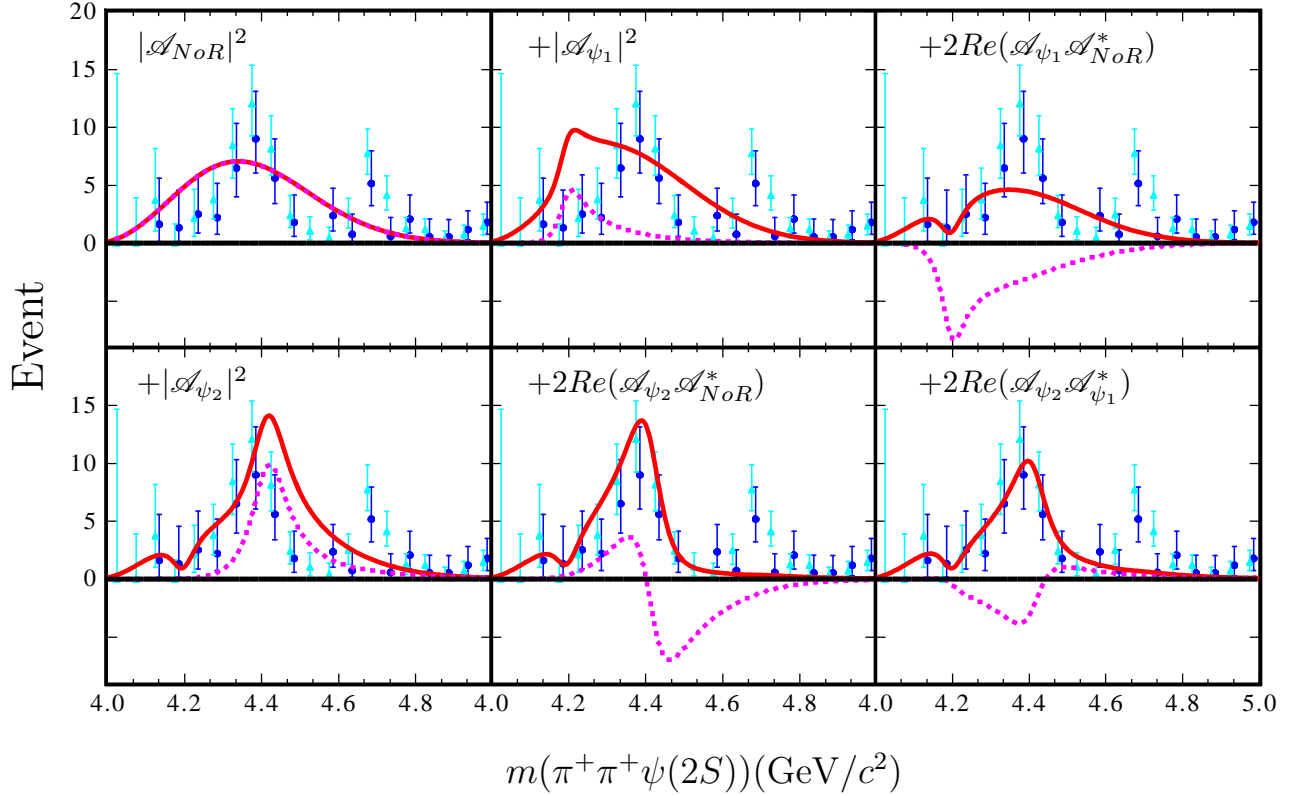[6] X. L. Wang *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 142002 (2007) [arXiv:0707.3699 [hep-ex]].

FIG. 2: (Color online.) The line shape of the cross section of $e^+e^- \to \psi(2S)\pi^+\pi^-$ process dependent on $\sqrt{s} = m(\pi^+\pi^-\psi(2S))$. The blue and cyan points with error bar are experimental data measured by BaBar and Belle, respectively. Our result is normalized to the experimental data. Here, one also presents the changes of the theoretical line shape (red solid line) by adding the contributions from these six terms ($|\mathscr{A}_{NoR}|^2$, $|\mathscr{A}_{\psi_1}|^2$, $2\mathrm{Re}(\mathscr{A}_{\psi_1}\mathscr{A}_{NoR}^*)$, $|\mathscr{A}_{\psi_2}|^2$, $2\mathrm{Re}(\mathscr{A}_{\psi_2}\mathscr{A}_{NoR}^*)$ and $2\mathrm{Re}(\mathscr{A}_{\psi_2}\mathscr{A}_{\psi_1}^*)$) one by one. The sum of such six terms finally results in the total line shape of the cross section of $e^+e^- \to J/\psi\pi^+\pi^-$ process just shown in the last diagram. The pink dashed line in each diagram reflects the contribution of each of six terms in $|\mathscr{A}_{tot}|^2$.

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